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Implementing Solar HVAC Systems in Schools

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Abstract—**Schools are unlike any other commercial property since they have special energy needs. High heat and electricity loads are the main key elements faced by design engineers. By implementing renewable energy for heating, ventilating and air conditioning (HVAC) in schools, a significant amount of energy savings can be achieved and this will also contribute in reducing gas emission. All power plants generating electricity today produce gases and waste that have a negative impact on the environment. During the summer the demand for electricity increases dramatically because of the extensive use of HVAC systems, this increases the peak electric load, causing major problems in the national electric supply system. Acknowledging that global warming is the number one environmental threat, because of gas emission, puts a serious pressure on mankind to reduce carbon dioxide (CO_2) emission to the atmosphere. High fuel prices force decision makers to adopt and encourage renewable energy resources. Implementing renewable energy might be a way to reduce the demand for electricity. In addition, most renewable energy systems are being developed in ways that reduce the need for convention fuel. This study presents a thorough review on ‘‘zero emissions’’ technologies for the built environment. The specific attention is given for subtropical climate in Australia. Both technical and economic feasibility compared to only grid connected HVAC are also discussed. This study contributes to the understanding and process development for implementing solar assisted HVAC systems in buildings in Jordanian climates**

Keywords:- Component; Renewable Energy; HVAC; Entertainment Centres; Zero Emissions.

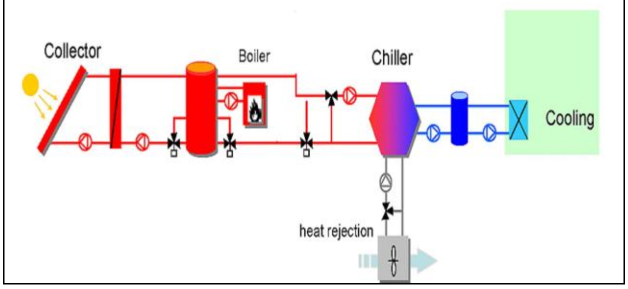
I. INTRODUCTION

Energy needs of a schools can not be compared with typical consumption of any other building (commercial or residential) because the energy needs is largely dependent on the specific event activity. Normally in schools the peak of required energy occurs after normal working hours or when offices are closed. Energy consumption usually depends on the time table of the center and event public attendance. Entertainment center air conditioning is one of the major consumers of electrical energy due to the high number of people attending a performance and the instruments used during the event.

Associated with air conditioning’s high use of energy is significant environmental pollution, in the form of greenhouse gas emissions with the resultant climate change impacting not only upon our environment, but also our health and productivity [1]. Of the many ways of individually addressing air conditioning’s impact upon the grid and environment, solar air conditioning is one of the few solutions that provides cooling and addresses the demand of peak loading, and does so with reduced environmental impact. Solar air conditioning is a way to reduce the demand for electricity which means less demand for fuel and coal. In addition, many solar air conditioning systems are constructed in ways that eliminate the need for chloroflurocarbons CFC, Hydrochlorofluorocarbons HCFC or Chlorofluorocarbons HFC refrigerants. Alternatives to use solar energy is waste heat from different industrial processes such as refineries, garbage treatment facilities etc. [2]. Energy costs, for example, which typically represent up to 10 percent of a center’s operating budget, can be reduced easily by 30% to 35% according to Fried Gil from sport facility management second edition [2-3]. Almost all schools treat energy costs as ongoing, uncontrollable costs extracted from core funding. By reducing energy costs, schools can keep more money for core funding and increase their discretionary spending [4]. This study presents why and how solar cooling technologies contribute to achieve energy and monetary savings and to reduce green house gas emissions.

II. WHY SOLAR COOLING?

During the summer the demand for electricity increases because of the extensive use of HVAC systems, which increase the peak electric load, causing major problems in the electric supply. The energy shortage is worse during ‘dry’ years because of the inability of the hydroelectric power stations to function and cover part of the peak load. The use of solar energy to drive cooling cycles for space conditioning of most buildings is an attractive concept, since the cooling load coincides generally with solar energy availability and therefore cooling requirements of a building are roughly in phase with the solar incidence. Solar cooling systems have the advantage of using absolutely harmless working fluids such as water, or solutions of certain salts. They are energy efficient and environmentally safe. They can be used, either as stand-alone systems or with conventional air conditioning, to improve the indoor air quality of all types of buildings. The main goal is to utilize "zero emission" technologies to reduce energy consumption and CO_2 emissions [5]. The schematic diagram of a solar air conditioning system is shown in Fig. 1.



. Figure 1 Standard system schematic [5].

III. TECHNOLOGIES APPLICABLE FOR SOLAR THERMALLY DRIVEN COOLING

Cooling can be obtained from many different ways. The majority of them have a direct or indirect origin with the sun, such as fossil fuels. The expression “solar cooling” is usually restricted to when the solar radiation is the direct agent of cooling. In order to evaluate the potential of the different solar cooling systems, a classification has been made by [6] names air conditioning systems, solar heat is required to drive the cooling process. Thus, solar assisted air conditioning systems operated so far may be classified into two types: closed systems and open system, where closed system these are thermally driven chillers which provide chilled water, that is either used in air handling units to supply conditioned air (cooled, dehumidified) or that is distributed via a chilled water network to the designated rooms to operate decentralized room installations, e.g. fan coils. Market available machines for this purpose are absorption chillers (most common) and adsorption chillers (a few hundred machines worldwide, but of rising interest in solar assisted air conditioning). Open systems; allows complete air conditioning by supplying cooled and dehumidified air according to the comfort conditions. The “refrigerant” is always water, since it is in direct contact with the atmosphere. Most common systems are desiccant cooling systems that use a rotating dehumidification wheel with solid sorbent as reported in J Peeples [7]. According to M Delorme [8], it has been possible to calculate the COP of the chiller based on the available temperature and flow measurements according the following formulas:

$$COP_{solar}=\frac{Qc}{Qh}=\frac{Qc}{Qr-Qc} \qquad (1)$$

Where

Qc	Cooling capacity
Qh	Heat capacity
Qr	Reject capacity

$$COP_{solar}=\frac{1}{\left(\frac{Qr}{Qc}-1\right)} \qquad (2)$$

$$Qc=m_c C_p\left(\theta_2(t)-\theta_3(t)\right) \qquad (3)$$

$$Qr=m_{CT} C_p\left(\theta_4(t)-\theta_5(t)\right) \qquad (4)$$

Where

$\theta i(t)$	Temperature at the local i and time t
m_{CT}	Water flow rate of the cooling tower
C_p	Specific heat of water

IV. FUNDAMENTALS OF SOLAR COOLING

A. *Open cycle processes (Desiccant solar cooling)*

Open cooling cycles produce directly conditioned air. Any type of thermally driven open cooling cycle is based on a combination of evaporative cooling with air dehumidification by a desiccant, i.e., a hygroscopic material. Again, either liquid or solid materials can be employed for this purpose. The standard cycle which is mostly applied today uses rotating desiccant wheels, equipped either with silica gel or lithium‑chloride as sorption material (fig. 2). All required components, such as desiccant wheels, heat recovery units, humidifiers, fans and water‑air heat exchangers are standard components and have been used in air conditioning and air drying applications for buildings or factories since many years.

Figure 2 Desiccant wheels [9].

B. *Close cycle process*

These are thermally driven chillers which provide chilled water, that is either used in air handling units to supply conditioned air (cooled, dehumidified) or that is decentralized room installations, e.g. fan coils. Close cycle consist of the following:

1) Absorption chillers: Absorption chillers offer an exciting alternative to conventional compression chillers, since their main energy input is heat instead of mechanical power. Fig. 3 shows the schematic of an absorption cycle. Absorption chillers come in a large variety of models and types, frequently requiring heat in the form of water vapour, or even direct fire. Applications with vapour frequently fit most waste heat rejection found in industrial processes such as combination heat and power. The COP is defined as in compression chillers but with the driving heat replacing the mechanical/electrical input. Traditionally absorption chillers are large machines with a large cooling capacity. Absorption chillers work much like conventional compression chillers, except that there is no mechanical compressor. Instead, the vaporised refrigerant leaves the evaporator to the absorber where it is diluted by a solution. The liquid solution is then pumped (pumps are more efficient than compressors), and then regenerated with heat (in the generator), so that the refrigerant is vaporised again, at a higher pressure and temperature. It then goes to the condenser to release the contained waste heat. Typically for chilled water temperatures less than 5°C, ammonia is used as the refrigerant and water as the absorber. For typical air-conditioning applications (chilled water above 5°C), the combination of water as refrigerant and lithium bromide (LiBr) as absorbent is more popular, while chillers using Ammonia as absorbent are more suited for industrial refrigeration, producing chilled water down to –10ºC [5]. The condenser’s heat rejection is again critical to the COP of the chiller.

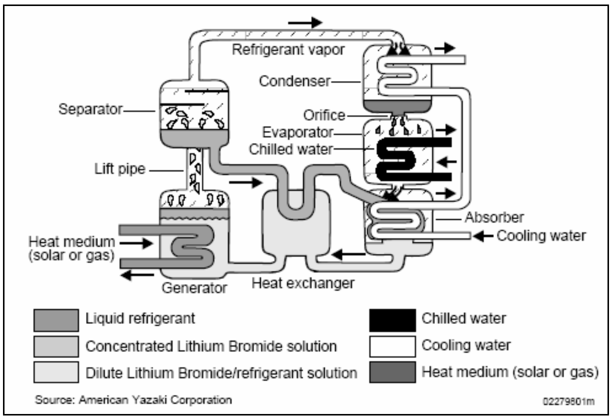


Figure 3 Absorption cycles [10].

2) Adsorption chillers: These chillers are similar to absorption chillers, since both are driven by heat. However, adsorption chillers can be driven by hot water at lower temperatures than absorption chillers, thus benefiting from a better efficiency on the solar collectors system because they are generating water at a lower temperature. The adsorption cycles is shown in Fig. 4. From a physical point of view, both technologies differ significantly since the sorbent used in adsorption is silica gel, a solid that cannot be compressed or pumped. Instead, each compartment containing the solid sorbent is alternately heated and cooled to adsorb and desorb the refrigerant in a periodic process. An adsorption chiller consists of two compartments on which the internal surfaces are covered with silica gel; a highly porous solid that captures water vapor (adsorbs the refrigerant). The same compartment is then heated (regenerated) with the driving hot water at temperatures ranging from 55°C to 95°C. The refrigerant at a higher temperature moves to the condenser where it is condensed, resulting waste heat that must be dissipated. A throttle valve drops the pressure of the condensed water to the level of the evaporator. At that low pressure, it receives enthalpy from the chilled water and evaporates, moving on to the other compartment, with the regenerated silica gel, thus completing the process. A cycle can take around seven minutes and it begins where the refrigerant goes to the evaporator, where it is evaporated with a strong vacuum, and produces chilled water. Then the refrigerant moves to one of the compartments filled with recently regenerated silica gel, where it is adsorbed. Then the cool/ hot water cycle inverts. Now heat is being supplied to the compartment, regenerating the silica gel. Back as in vapor form, the refrigerant is pressurized and goes to the condenser. And in the condenser, chiller condensates releasing waste heat (to be dissipated). The liquid refrigerant is then sprayed back to the evaporator completing the cycle [11-13].

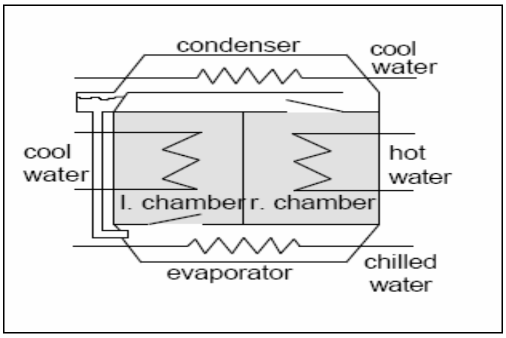


Figure 4 Adsorption cycles [10].

V. SELECTION OF THE APPROPRIATE SOLAR AIR CONDITIONING TECHNOLOGY

A general system scheme which contains both, open desiccant cycle and closed cycle water chillers, is shown in Fig. 5. Solar thermal heat is provided to both applications. The scheme includes different backup system options as well: on the heat side by other heat sources (e.g., gas burner, connection to a district heating network or co - generation plant, etc.) and on the chilled water side a backup compression chiller. A realized system with solar thermal assistance usually consists of a sub - system of this Figure according to the solutions, following the different paths in the decision scheme. These sub - systems are outlined as follows.

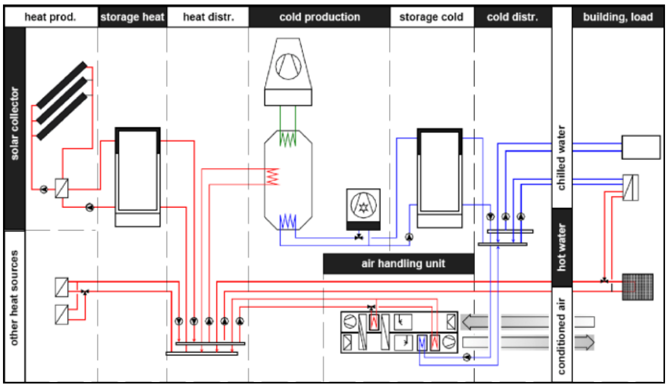


Figure 5 General scheme of a complete system including desiccant technique and thermally driven water chiller [10].

A. *All air system:*

It is considered that the installation of a centralized supply/return air system is feasible and the required air change rate is sufficient to cover all sensible and latent cooling loads. In this case, an all air system is possible; no other cooling equipment is required. A precondition is a tight and very well designed building with measures to reduce the cooling demand, such as use of energy saving equipment, efficient shading, minimizing artificial lighting through day lighting concepts, night ventilation (e.g., in combination with phase change materials), etc.as in Fig. 6. Another example is a lectures room with a high occupation rate; in such room the required fresh air amount may be high enough to purge the sensible loads completely. The installation site is considered in a moderate, continental climate with temperate outdoor humidity and temperature conditions. Thus, a standard cycle of a desiccant evaporative cooling (DEC) system is applicable. The solar thermal collector system provides heat for the regeneration of the dehumidification unit as well as for supply air heating support in winter. A backup heat may be necessary in winter and to provide additionally regeneration heat to the dehumidification unit, in case the collector power is low but dehumidification is still necessary.

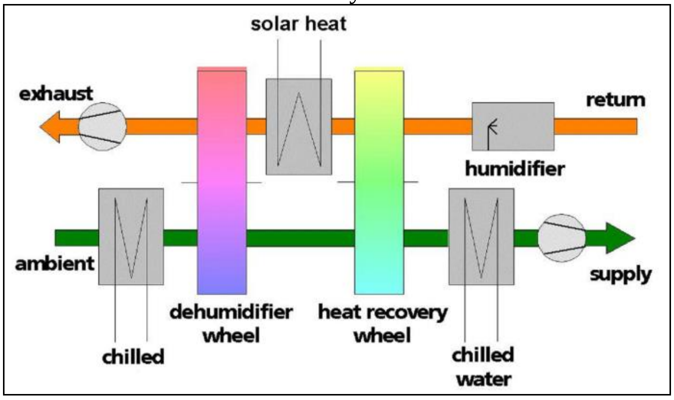


Figure 6 all air system [10].

B. Supply air system and chilled water distribution:

It is considered that a central air handling unit is desired, however, in a building which is not sufficiently tight, the installation of a supply/return air system is problematic since either outside air is sucked into the building (internal pressure lower than external), or is lost through the building shell (internal pressure higher than external). In such a case an air handling unit to provide fresh air only would be installed. Fresh air is cooling and dehumidified and sensible loads not covered by the fresh air are purged by other means. An example might be a chilled ceiling system. Configuration and a possible realization sketch is shown in Fig. 7. A thermally driven chiller, operated with solar heat, supplies chilled water to the air handling unit and to decentralized cooling installations via a chilled water network. Dehumidification is realized in the supply air handling unit. Thus, the chilled water temperature has to be sufficiently low. The chilled water delivered to e.g. chilled ceilings is to be mixed to higher temperatures by controlled valves. The technology shown in Fig. 7 is in general applicable in extreme climates[14-16].

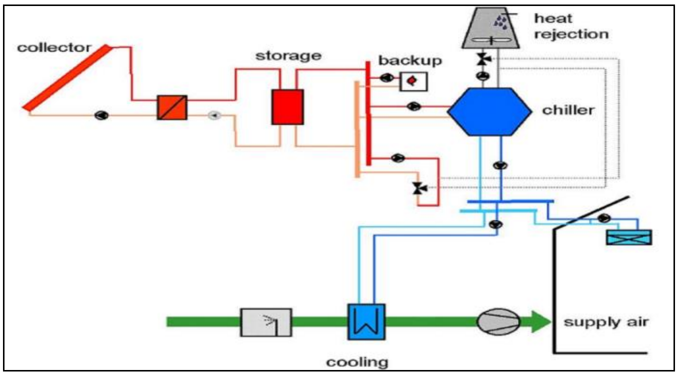


Figure 7 air system and chilled water distribution [10].

C: All Water systems: In case the installation of a centralized air handing unit is not feasible or desired, the only technical solution to use solar thermal energy for building 3 (a case study building for this study) is the installation of a thermally driven chiller to supply cold water to a chilled water network. Independently from the climate conditions, a low temperature of the chilled water (approximately between 6°C and 9°C) is required in order to allow for air dehumidification in a fan-coil system. This technical solution is shown in Fig. 8. The driving source for the chiller is a solar collector system. At least high quality flat plate collectors are required to provide heat to the chiller, which either can be, an adsorption or an absorption chiller. Generally, does not support de humidification process due to the difficulty of installation a desiccants wheel since there is no air handling units.

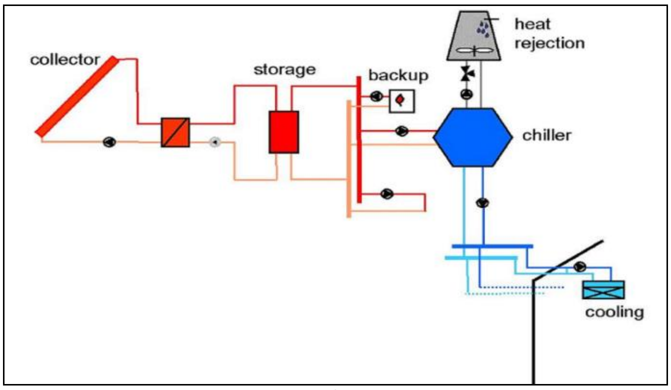


Figure 8 Decision paths for an all water system

VI. SOLAR COLLECTORS

The collectors' efficiency drops as the working temperature gets higher. To work at the temperatures required for solar air-conditioning, the collector' heat losses must be as small as possible. Due to the temperatures involved, solar collectors' efficiency should not be calculated by a normal linear relation, but by a polynomial expression of 2nd order to account with the losses by radiation to the sky as in (4) [8]:

$$\eta = k(\Theta).c_0 - \frac{(T_{av} - T_{amb})}{G_p}.c_1 - \frac{(T_{av} - T_{amb})^2}{G_p}.c_2 \qquad (4)$$

Where $k(\Theta)$ is the incident angle modifier, T_{av} is the average fluid temperature, T_{amb} is the ambient air temperature, and G_p is the total global radiation incident on the collector surface. The remaining constants are indicated in Table 1, which presents diverse typical parameters for the most usual types of collectors [8].

TABLE I SOLAR COLLECTORS TYPICAL PARAMETERS [11]

	Evacuated tube collector 1	Evacuated tube collector 2	Flat plate collector 1	Flat plate collector 2	Stationary CPC collector	Roof integrated collector
Gross area	1.181	2.762	2.567	2.612	2.69	6.082
C0	0.612	0.601	0.690	0.696	0.556	0.704
C1	0.54	1.44	2.61	3.26	1.30	3.03
C2	0.0017	0.0033	0.0098	0.0062	0.0195	0.0096
? (?T=50K)	57.3 %	50.0 %	49.7 %	47.3 %	41.3 %	48.5 %
? (?T=70K)	55.4 %	45.4 %	40.3 %	37.4 %	32.2 %	38.0 %
€/m^2	643	555	234	234	223	175

VII. PRIMARY ENERGY SAVINGS

Any type of air-conditioning and cooling is connected to the use of primary energy sources, to provide electricity or heat in order to operate the end-user equipment. Today, the primary energy sources used in most of the countries are predominantly composed of fossil fuels and thus their use is linked with greenhouse gas emissions. Consequently, the basic requirement on a solar air conditioning and cooling system is the saving of primary energy and reduction of greenhouse effect supporting emission. This pre-condition effects the configuration and design of solar air-conditioning and cooling systems; this is discussed in the following example. We consider a solar thermally assisted cooling system with a fossil fuel gas boiler as back-up heat source and compare the primary energy input with a conventional electrically driven vapor compression chiller system. The backup heater is foreseen in order to cover the heat demand of the chiller in periods of low solar heat availability but still present cooling demand. Boundary conditions in this comparison are:

- Space heating is not considered
- In the reference system, energy input for dry heat rejection is included in the Coefficient of Performance of the vapor compression chiller COP_{VCC}. In the solar assisted system, the thermally driven chiller is characterized by the thermal coefficient of Performance COP_{TDC}. Energy effort for heat rejection is considered separately.
- Specific primary energy demand per kWh useful cold are calculated based on the estimated average consumption data and conversion numbers.

The governing formulas 5-11 are, to estimate the primary energy demand are thus given in the following [17].

$$PE_{C.sol} = \frac{1-SF_c}{\eta_{boiler} \times \eta_{PE,\,fossil}} + \frac{SF_c \times f_{el,solar}}{\eta_{PE,grid}} + \frac{COP_{TDC} \times f_{el.TDC}}{\eta_{PE,grid}} + \frac{f_{el.HR} \times (COP_{TDC}+1)}{\eta_{PE,grid}} \quad (5)$$

Then Energy demand from fossil source

$$= \frac{1-SF_c}{\eta boiler \times \eta PE,\ fossil}$$

(6)

Electricity energy for solar system

$$= \frac{SF_c \times f_{el,solar}}{\eta_{PE,grid}}$$

(7)

Electricity for thermal driven chiller

$$= \frac{COP_{TDC} \times f_{el.TDC}}{\eta_{PE,grid}} \quad (8)$$

Electricity of heat rejection

$$= \frac{f_{el.HR} \times (COP_{TDC}+1)}{\eta_{PE,grid}}$$

(9)

While equation 10 represents the reference system energy demand ($PE_{c,ref}$)

$$PE_{c,ref} = \frac{Q_C}{COP_{VCC} \times \eta_{PE,grid}} \quad (10)$$

And Primary energy saving (ΔPE_{ref}).

$$\Delta PE_{ref} = \frac{PE_{c,ref} - PE_{C.sol}}{PE_{C,ref}} \quad (11)$$

TABLE II EQUATION 5-11 SYMBOLS

Symbol	Definition
$PE_{C.sol}$	The primary energy demand of solar cooling system.
COP_{TDC}	Coefficient of performance of thermally driven chillers.
COP_{VCC}	Coefficient of Performance of the vapour compression chiller.
Q_C	Cooling capacity.
SF_c	Solar fraction of driving heat to thermally driven chiller.
$\eta boiler$	Efficiency of fossil fuel boiler
$\eta PE,\ fossil$	Primary energy efficiency of fossil fuel.
$\eta_{PE,grid}$	Primary energy efficiency of electricity grid.

$f_{el,solar}$	Specific electricity demand of thermally driven chiller.
$f_{el.HR}$	Specific electricity demand for heat rejection

The general dependency between the primary energy demand and the solar fraction is displayed in Fig. 9. The primary energy demand is shown per unit kWh produced cold. The demand for the reference system depends on only, thus results in horizontal lines. The primary energy demand for the solar assisted system decreases with increasing solar fraction, but varies with the thermal. Exceeding a certain solar fraction, the primary energy demand of the solar assisted system falls below the primary energy demand of the reference system, and the solar thermal driven solution saves primary energy. Consequently, the system has to be designed in an appropriate way to guarantee the average solar fraction in the cooling period.

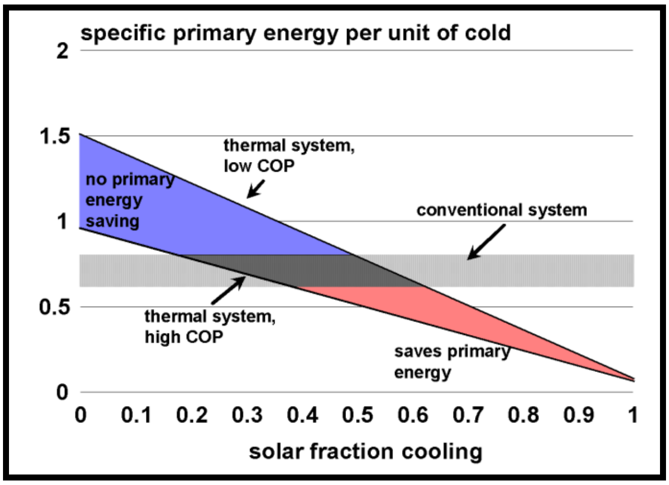


Figure 9 primary energy savings [8].

VIII. FINANCIAL PERFORMANCE

The financial performance of solar cell assisted air conditioning must be evaluated to determine whether or not it is providing economically viable services. To do this, operating expenses, current and projected cash flows, including capital expenditures needs to be monitored and assessed. This information is then used to determine the current and projected economic return of the asset or portfolio. Cash Flow analysis can be used to provide a measure of the Net Present Value and the internal rate of return for assets. Solar processes are generally characterized by high investment and low operating cost. The cost of any energy delivery process includes all the items of hardware and labour that are involved in the installation of the equipment, plus the operating expenses. It is vital to determine the primary energy savings and relevant costs for different solar system. The economic analysis methods such as the net present worth, the benefit cost ratio, the rate of return and the payback period are suitable to evaluate single retrofit options. However, life cycle analysis methods are appropriate to select most economic options among multiple retrofit alternatives [12].

A. Collector first cost

A simple calculation can be performed considering the collector efficiency curve obtained according to [8] by using (12):

$$\eta = \eta_0 - a_1 \times \frac{t_m - t_a}{G} - a_2 \times \frac{(t_m - t_a)^2}{G} \qquad (12)$$

Where η_0 = Optical efficiency, a_1, a_2 = Collector heat loss coefficient, t_m = Collector temperature, t_a =Ambient temperature.

The power delivered by the solar collector operating at a temperature t_m is:

$$q = A\eta G \Rightarrow A = \frac{q}{\eta G} \qquad (13)$$

The collector area per kW power produced is given by (14):

$$A_{spec} = \frac{1Kw}{\eta G} \qquad (14)$$

If a collector has 50% efficiency at an average temperature of 80ºC and considering that the irradiance incident on the collector is 800 W/m², the collector specific area, i.e., the area necessary to produce 1kW power is 2,5 m². Considering the collector specific cost, based on information of current solar thermal systems installed, i.e., the collector cost per collector area, the cost of collectors per power unit produced can be determined by (15):

$$Cost_{heat,Power} = A_{Spec}\,Cost_{Spec} \qquad (15)$$

All calculations made until this moment considered only power produced by the collector. Solar Thermal collectors do not produce a constant power, but a variable power which depends of the variation of the irradiance incident on the collectors due to variation of weather conditions. The annual cost of the heat produced by the solar thermal system (Solar heat cost) can than be calculated according to (16):

$$Cost_{Anual} = Cost_{Spec} \times f_{annuity} \qquad (16)$$

where $f_{annuity}$ is the annuity factor that takes into account the interest rate of the investment and the lifetime of the collector system.

$$Cost_{heat} = \frac{cost_{annual}}{Q_{gross}} \qquad (17)$$

where Q_{gross} is the annual collector heat production at a given site and a given operation temperature[19-20].

B. Evaluation of the annual savings and over cost evaluation

The reference solution to calculate the savings is based on the technology which would be used if the solar system was not implemented. The amount of saved energy is quantified because it represents the gain between a solar system and a reference one. In the majority of the cases, the investment of a conventional solution as a back up is however necessary to face the load when the sun is not present. So, it can not be considered as a kind of saving. Equation (18) represents solar energy annual savings:

Annual savings = cooling energy × cost of useful kWh (18)

Where useful solar energy represents the amount of energy produced by the solar system and available for the cooling load. The reference solution to calculate the over cost of the solar system is based on the technology which would be used if the solar system was not implemented. In the solar cooling projects, the working and maintenance costs are not taken into account because they are estimated to be at the level of the ones of a reference solution[20-22].

Over cost= Solar project cost-Reference solution cost (19)

IX. CONCLUSIONS

Solar cooling has the potential of significantly reducing the electricity consumption of schools under Jordanian climates . Although most of the current solar cooling applications are demonstration projects in nature, the technologies are mature. Research and development activities are concentrated in improving the COP as well as making the equipment smaller in size and more affordable. It is of vital importance to select the right equipment for each application depending on the desired performance specifications. Careful analysis of internal loads is required to size and specify the equipment correctly. Centres operators and other stakeholders need to break free from considering only the financial payback and embrace the long term benefits of solar cooling that contribute towards energy independence and environmentally friendly goals in a larger scale. Solar assisted air conditioning is a new and growing technology, compared to other fields of solar energy application. The novelty of this technology is reflected by the fact that most of today’s realized projects are of demonstration nature and still a lot of additional design and planning effort is required in the implementation phase of such a project. Various technical solutions are possible, depending on the type and use of the building, on boundary conditions like e.g. existing technical infrastructure, and on other like e.g. climate conditions [5].

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